The Quantum View of the World

I want to show in this talk how philosophical problems and scientific problems interact in the understanding and interpretation of quantum mechanics. To some of you QM may appear to be just a set of rules for calculating numbers to compare with pointer readings in a idealized version of experimental physics. And if the numbers agree with the pointer readings that is all there is to 'understanding' QM. But from the outset physicists like Einstein, Schrödinger de Broglie (and perhaps Bohr), sought to go beyond this 'instrumental' interpretation (see Stapp)) and to provide a conceptual understanding of QM (to be distinguished from a picturable model like the famous ether models used in trying to understand 19th Century electromagnetism.)

One of the first things you learn in elementary courses on QM is that the uncertainty relations that you cannot measure simultaneously so-called non-commuting observables like momentum and position. If you try to measure one you disturb previous knowledge of the other, and was explained rather picturesquely in the famous thought-experiment of the γ-ray microscope.
But even if you cannot measure simultaneously does this mean that there is nothing there, ontologically speaking, to be measured.

Insert
✱ There is a third view, essentially that of Bohr, that 'the momentum is not defined at all' in an eigenstate of position, that talk of the electron possessing genuinely an unsharp value of momentum is 'a dangerously misleading way of describing the situation', that 'momentum is only defined relative to an experimental arrangement designed for producing eigenstates of momentum, that experimental arrangements which produce eigenstates of position leave talk of momentum essentially meaningless since the term lacks definition' as Bohr puts it. There is a lot of ambiguity in Bohr's text here whether to mean lack of definition in the semantic sense that no meaning can be attached to the momentum (a positivistic approach to the meaning of unobservable quantities) or lack of fixation in the concept which suggests rather a new ontology of unsharp values as referred to the second alternative referred to above.

②

In an eigenstate of position does the momentum have a value although we don't and indeed can't know it, or does it just not have a ~~value~~ sharp value at all but a fuzzy or overlapping one which is only rendered sharp by a subsequent measurement of momentum. I.e. if we measure momentum in an eigenstate of position do we discover something already there or create something new, a sharp value, out of something essentially different, an unsharp value. * At first sight these might appear to be a priori metaphysical questions having no empirical significance. The remarkable thing is that QM does enable us to do what I shall call [~~theoretical~~ ;] experimental ontology even in the absence of direct observational confirmation [~~Let me explain: ontology~~] The situation metaphysically is not unlike 19th Century kinetic theory. Nobody could see atoms and molecules, but ~~their~~ assumed existence had remarkable empirical consequences, laws of gases, specific heats, transport properties of gases etc. If we cannot establish an ontology, perhaps we can rule it out by experiment (there are some rather subtle points here about falsifying existential claims that I will not go into). Recent experimental work in quantum mechanics is widely interpreted as compelling us to abandon one or other of two widely cherished principles, the existence of an independently existing external reality or the principle of so called Einstein locality, that physical effects cannot be produced over space-like intervals in spacetime. I want to examine this claims. First a little bit of history, then a little bit of physics, and finally a little bit of philosophy.

In 1935 EPR put forward a argument for the incompleteness of QM that there must be antecedently existing elements of reality corresponding to the position of an electron in a Hamiltonian eigenstate for example. [~~But in 1932 von Neumann in his famous book The Mathematical Foundations of QM had already 'proved' that QM could not be 'completed' in the sense of admitting a more precise state-specification in terms of so-called hidden variables relative to which the precise values demanded by the EPR argument could obtain.~~

~~But there were assumptions in both the EPR argument & the von N. argument which might be challenged. Taking these two results together one would logically conclude.~~

~~QM → incompleteness~~ EPR.

~~But completion → ~QM.~~ Van N.

~~So QM must be false.~~

~~But there were assumptions in both the EPR argument and the von Neumann argument which might be challenged.~~

~~EPR assumes locality: an unsharp value could not be turned into a sharp value by space-like connection.~~]

P.T.O.

Insertion
*

Bohr's response (1935) was essentially that the violation of locality, involved a non-physical effect, viz. turning an undefined ~~object~~ value into a defined one. We shall refer to this as non-locality of the zero-kind – its denial would be locality_0. We cannot say for Bohr that definability (⇔ predictability) is at all the same thing as definiteness (⇔ predeterminedness)

The argument involved however a locality assumption what I shall call locality₁: an unsharp value cannot be turned into a sharp value by 'space-like' causation

So - QM + locality₁ → incompleteness

* We can now now take 2 [illegible] [illegible] equivalent
QM → (non locality₁) ∨ (incompleteness)

Let us for the moment take the first horn of the dilemma as blocked.

If QM is incomplete, then clearly we should try to 'complete' it

But various proofs that this was not possible appeared in the literature

QM + completion → contradiction

cf. Von Neumann 1932 in his book Mathematical Foundations of QM.
– But there are additional assumptions evident in any such proof.

So QM + completion + ? → contradiction

Bell (1966) criticised von N's assumption and relaxed them by others also Kochen, Specker (1967) that 'functional relationships among commuting observables should be preserved for the assignments.

(4

[~~Von N. assumes a quite unreasonable~~
~~So QM + locality → incompleteness~~
~~If we deny locality, we can escape~~
~~the EPR [illegible]~~ -]

thus Von. N. assumes a quite unreasonable additional assumption on expectation values of non-commuting operators for dispersion free states specified by hidden variables. This was first clearly pointed out by J.S. Bell in 1966. ~~A~~ Revisions of the von N. No-hidden-variable theorem were rapidly supplied in rather different formulations by Bell 1966, Kochen & Specker 1967. K & S showed that assuming a rather natural functional composition principle relating the values assigned to observables and functions of observables one could derive a logical contradiction from value assignments in Hilbert spaces of dimension ≥ 3 - the crucial point here is the role played by degenerate observables in 2-dimensional Hilbert space the degenerate observables are trivial and [illegible]. [~~But again there is a hidden assumption of Non-Contextuality that the result of measuring a specific observable does not depend on what other observables are being measured at the same time.~~

~~So we have:~~

~~QM + Completeness + FM + N.C. + ~~QM~~ F.C. → Contradiction.~~

~~But FM + N.C. ⟹ F.C.~~

~~So we have to choose between ~~QM~~ (QM false) / (Bell, Bohm, Hiley)~~
~~completeness (von Neumann)~~
~~Contextualism~~
~~~FM~~ RP]
~~~

~~[illegible] products of DM involved in the argument to identification of offenders and self-report offenders on [illegible] [illegible].~~

~~[illegible] Have we gone inside the statistical objectives of DM in addition to the mere identification of offenders and other offenders and in the [illegible] [illegible] pred.~~

~~[9.8 Predictions of QM invoked no more than its identification of observables with self-adjoint operators in Hilbert Space.]~~

~~[10 Here we have invoked the statistical interpretation of QM in addition to the mere identification of observables with self-adjoint operators acting in the Hilbert state space.]~~

So here we get.

QM + Completion + Func. → contradiction

But could we deny Func.? This is Fine's way.

But ~~Bell's answer is~~ another answer is possible (van Fraassen (1973) after Bell (1966))

Reject CORR: observables and operators are in 1:1 correspondence

this leads to deoccamized version of QM.

What we are really dealing with in K-S proof is

CORR. + Completion + Func. → Contradiction

But so far we have only used CORR. in the argument. What about the rest of QM in particular the statistical algorithm for calculating probabilities and expectation values.

For two separated spin-½ systems Hilbert-space is 4-dimensional so we need some deoccamization but not for spin components & local Hilbert operators (and the observables that stand in the joint Hilbert space like $\sigma_1 \cdot \sigma_2$ etc)

N.B. Even having dealt with K-S paradox by relaxing Func. (via destabilising CVD.) and the Bell paradox by denying Locality one still may not be able to give a hidden-variable phase space reconstruction

$$\langle Q\rangle_{\psi QM} = \int [Q]^{\psi}(\lambda)\rho(\lambda)d\lambda$$

for all Q since this implies the existence of joint probability distributions for non-commuting observables

$$\mathrm{Prob}\left([Q]\in\Delta \wedge [P]\in\Delta'\right)$$

$$= \mathrm{Prob}_\lambda\left[[Q]^{-1}(\Delta)\cap[P]^{-1}(\Delta')\right)$$

where $\mathrm{Prob}_\lambda(S) = \int_S \rho(\lambda)d\lambda$

But the existence of such joint distributions has been shown to be impossible by Cohen (1966), Nelson (1967) under a very mild form of FUNC. viz.

$$[Q^2] = ([Q])^2$$

which does not involve many-one mappings (if $\{[Q]\}$ is possible) and hence cannot lead to K-S paradox — although it does constrain non-commuting observables directly — in this sense the Cohen-Nelson proofs are stronger than the Kochen-Specker.

Now we can show that if assume locality$_2$ i.e. a sharp value cannot be turned into another sharp value at space-like separation that we can derive

Stat. Algorithm + Completion (+ sequential [illegible]) + locality$_2$ → contradiction.

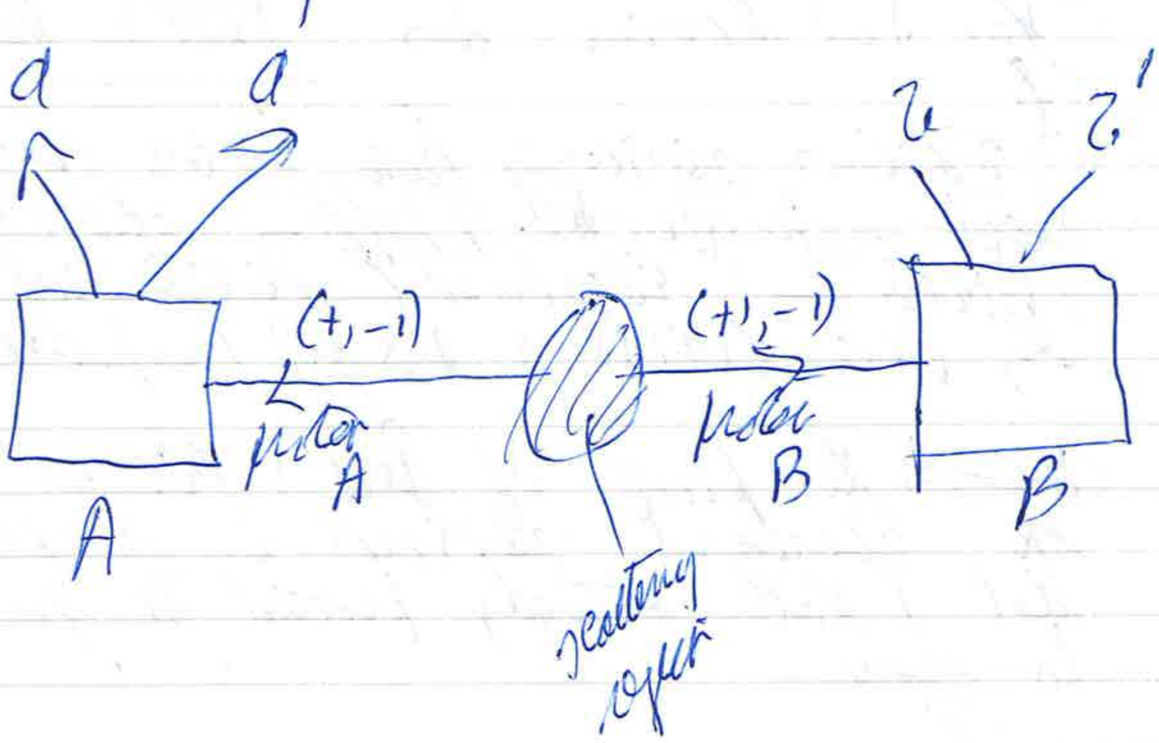
~~The original version of this theorem~~ thus is known as Bell's theorem.

& various versions from 1964 onwards Bell(1964) — Wigner(1970)-Bell(1971) — Stapp(1971) ~~Eber~~ Clauser, Horne(1974) — Eberhard(1977) (— ~~Peres~~ improved by Peres (1978) & Brody 1980 (unpublished))

~~Was~~ the proof of Bell's theorem in the Eberhard version is so simple that I shall actually proceed to present it to you.

X

[illegible]


a
a'
b
b'
(+1, −1)
(+1, −1)
photon A
photon B
A
B
scattering object

[~~Ans 1) QM^{FM} + Contextualism → incompatibility~~
~~Decohered version of QM does this.~~

~~But query 2) Does Contextualism → locality$_2$~~
~~We may introduce~~
~~label locality$_2$: a theory which cannot be turned into another theory which by space-like connection.~~

So ~~The QM does nonlocality$_2$ contextualism~~
~~[illegible]~~
~~Bell (1964) showed~~

~~QM + locality$_2$ contextualism → contradiction~~
~~+ contextualism~~

II

~~∴ nonlocal$_2$ contextualism is a conseq. of QM.~~

~~A further twist to the argument in 1964 ... Bell ... Stapp and Eberhard. Can we accept h-v. with contextuality and formulate nonlocality effects in macroscopic terms. Let us give the argument: — (call this locality$_3$: a macroscopic object cannot have its classical state altered by space-like connection~~]

We consider two protons, e.g., travelling apart after a low-energy collision ~~travel~~ in a singlet state of their total spin and suppose we measure their spin components in arbitrary directions
a, b in units of $\frac{1}{2}\hbar$ by suitably oriented Stern-Gerlach devices (in fact Lamehi-Rachti & Mittig did this experiment in 1976 using a scattering between

*

Smarter

~~*~~ better write

$\delta n = an(2n+2n') + 2n'(2n-2n^2)$

one factor must be zero and other term is always ±2. (cf Bleany) for identifying their spin components)

Let us suppose we can alter the settings of our two spin-meters from a, b to a′ b′ and we consider doing four sorts of experiment by taking either setting a, a′ in combination with either setting b, b′. We label the protons A, B (forgetting about the question of whether identical particles like protons can in any sense in QM be said to be individuals – another thorny philosophical problem), where the B proton moves towards spin-meter B with its two possible settings b, b′ and A moves towards the spin-meter A with its settings a, a′. Now the results of any of the four spin-measurement modes is according to QM always +1 or −1. To keep notation simple let us first of all assume that the spin values of each particle have a well-defined value in both ~~a a′ and~~ supposed, pinned directions – and we denote the spin component of particle A in direction a by a etc; so we can assume a, a′, b, b′ = ±1

Now let the nth proton pair ~~have~~ have values a_n, a'_n, b_n and b'_n, again all equal to ±1.
Now form the expression

$$\ast \qquad \gamma_n = a_n b_n + a_n b_n' + a_n' b_n - a_n' b_n'$$

Notice the 4th term is the product of the first 3 since $a_n^2 = b_n^2 = 1$

What values can γ_n take?
clearly each term have value ± 1
so γ_n is some integer between -4 & $+4$.

In fact it is easy to see that
$\gamma_n = \pm 2$. (eg writing $\gamma_n = a_n(b_n + b_n') + a_n'(b_n - b_n')$)

~~Free (i) we exclude $\gamma_n = -3, -1, 1, 3$ since 4 odd no's cannot add to an odd number.~~

~~(ii) we exclude $\gamma_n = \pm 4$ since the 4th term always has the opposite sign to the first contributes with the opposite sign to the first 3, if these all have the same sign~~

~~(iii) we exclude $\gamma_n = 0$ since the 4 terms can never cancel in pairs, as can easily be checked~~

So if we average $\frac{1}{N}\sum_n \gamma_n$

$$= |C(a,b) + C(a,b') + C(a',b) - C(a',b')|$$
$$\le 2$$

where $C(a,b)$ is the correlation function $\overline{a_n b_n}$

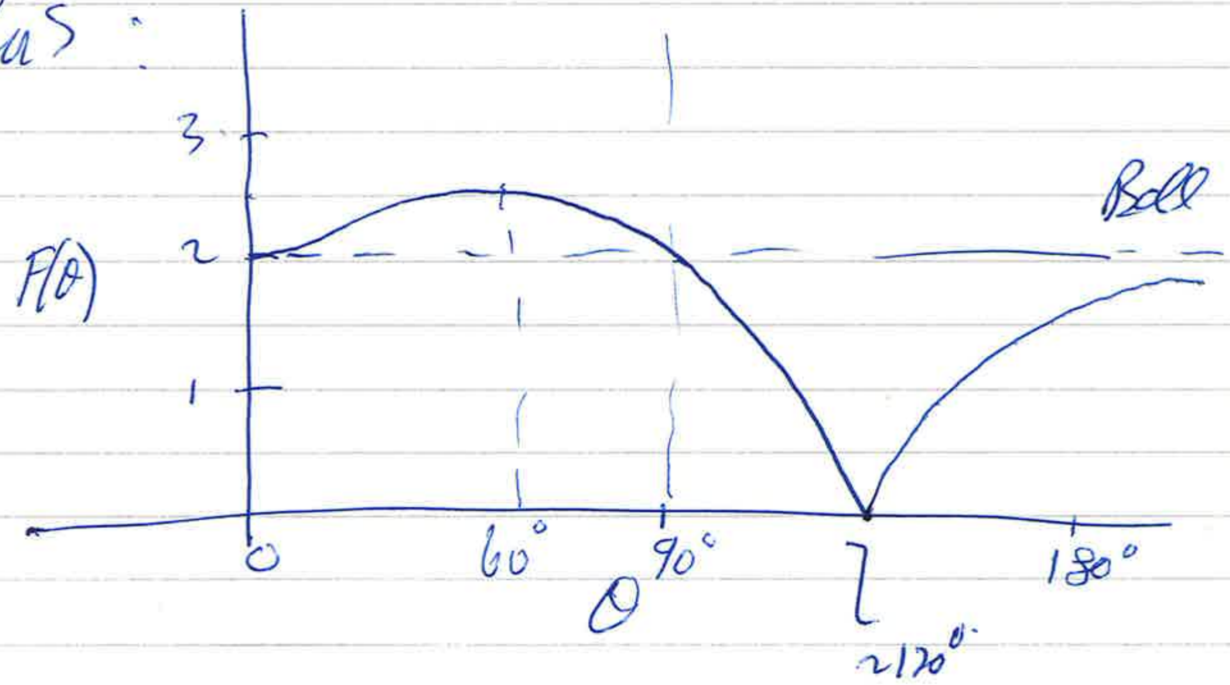
This result is known as Bell's Inequality ~~or Bell's Theorem.~~ It is well-known that it is violated by the quantum-mechanical correlation function for 2 spin $\frac{1}{2}$ particles in the singlet state for which
$C_{QM}(a,b) = -\cos\theta_{ab}$ where θ_{ab} denotes

the angle between the directions a and b

To see this in detail take $a = b$ as bisecting the angle 2θ between a' & b'. So, writing $F(\theta) = |C_{QM}(ab) + - - |$

we have in this instance
$F(\theta) = |1 + 2\cos\theta - \cos 2\theta|$
but this is > 2 for $0 < \theta < \pi/2$ so in this region Bell is violated

Thus:



For small θ
$F(\theta) \sim 2 + \theta^2 - - - -$

As an example of classical system that does not violate Bell's theorem consider two wheels rotating in opposite directions with equal magnitude angular velocity on an axle, which then separate by an explosion and measure the quantities
$P(a) = \text{sign}(J_1 \cdot a)$ and $P(b) = \text{sign}(J_2 \cdot b)$
for the two wheels here labelled 1 and 2. where J_1 is the angular momentum of wheel

number 1 and J_2 of wheel no 2.

then for zero total angular momentum $J_1 = -J_2$. but the quantities $P(a)$, $P(b)$ are clearly always +1 or -1. If the angle before the experiment varies its direction randomly over the unit sphere ~~[illegible]~~ it is easy to calculate the correlation functions ~~such a~~

$$C(a,b) = \overline{P(a)P(b)}$$

which comes out to be:

$$C(a,b) = -1 + \frac{2\theta_{ab}}{\pi}$$

Substituting in the special case of Bell's inequality we used above we now find at once:

$$F(\theta) = 2$$

i.e. the Bell inequality is saturated for all angles θ.

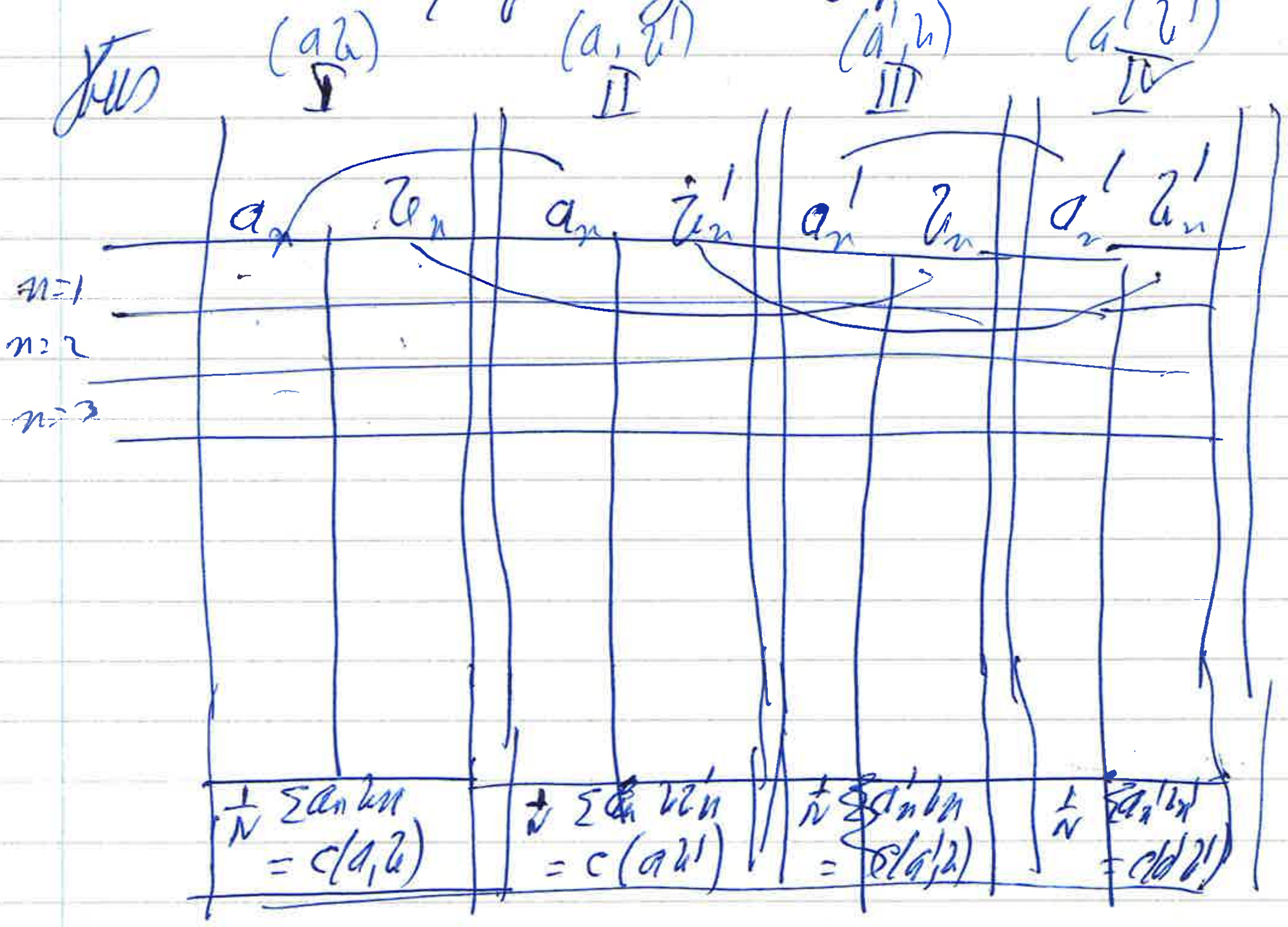
Notice how for small θ_{ab}

$$C_{QM}(a,b) = -1 + \frac{\theta_{ab}^2}{2}$$

compared with * it is clear that the quantum system 'hangs on' to the exact anticorrelation achieved for $\theta_{ab} = 0$ to a greater degree that is possible for a classical system — this is the source of the nonlocal character of the QM case that we shall now explore.

First of all ~~take the case~~ it is clear we cannot perform the 4 correlation experiments on each particle pair, i.e. for each value of n, but it makes perfectly good sense in a deterministic situation where a measurement just discovers what is already there to compute the observed correlations by averaging over *all* the entries in any of the four experiments.

Thus


(a, b) I
(a, b') II
(a', b) III
(a', b') IV
a_n b_n
a_n b'_n
a'_n b_n
a'_n b'_n
n=1
n=2
n=3
$\frac{1}{N}\sum a_n b_n = c(a,b)$
$\frac{1}{N}\sum a_n b'_n = c(a,b')$
$\frac{1}{N}\sum a'_n b_n = c(a',b)$
$\frac{1}{N}\sum a'_n b'_n = c(a',b')$

But now note the locality assumption ~~the~~ on a given row the ~~a~~ value is the same in expt I and in expt II similarly with a', b' ~~ent~~ each of which occurs in two columns corresponding to experiments which differ in the *remote* knob setting. If we give up this locality assumption the argument fails[2] but Eberhard has considered the case where the entries stand not for possessed values but for measurement outcomes results. Here we must be much more careful. If the measurement results are determined produced by revealing the possessed values then in the case locality₃ would be violated here as well by locality₃: A macroscopic object cannot have its classical state altered by space-like separated action initiated by another macroscopic object.

But suppose the class of measurement results is arising (undetermined), i.e. intrinsically stochastic out of a 'quantum state' then we have to abandon a very perfect condition (Stapp (1971)) of counterfactual definiteness: the result of a measurement not performed has a definite ~~value; which was~~ what would occur if it were performed

So.

* cf David Lewis: Counterfactuals (1973)

Bradley & Swartz: Possible Worlds (1979)

S. Haack: Philosophy of Logics
D. Lewis: Counterfactuals & Time's Arrow
Noûs 1979

Slote: Counterfactuals & Tense
J. Philosophy 1978

~~[But now suppose the plate-rotation alters the a, b values in a systematic way, i.e. changing b to b' alters the values of b' and also of a. The observed QM correlations might well be quite different from the conditions in Bell's inequality.~~

~~To see how this might conflict, a new table in which column II (from I) is the result obtained by changing b → b' in b-setting, III is obtained from I by altering a → a', and IV is obtained from II by altering a → a'. Notice it does not matter that b → b' alters the b' value — what is crucial is whether it alters the a value if it does the standard against collective [illegible]. Correlation functions are calculated from the recorded columns of values obtained by altering the local settings~~

~~We turn to consider the [illegible] of the argument. There are two versions.]~~

a) Counterfactual formulation*

Result of doing experiment II for a definite value is the same as experiment I if it had been done in place of I. i.e. the a value is the same.
But then by rotating to do what locality of the production of a, b angles is undetermined. If we let it seen on after altering b → b' in b setting we cannot infer that a value is the same and thus is not causally related to the way the b-setting is

before we alter that [illegible]

Ex I move my hand just before a atom
a little decays:
If I had not moved my hand
would the atom have decayed?

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2) Factual Formulation

Prepare table by running 4
separate experiments - List
4 columns I, II III, IV.
Now do place - selection on
rows [illegible] a values coincide
between I, II etc.
Then compute correlations on this
place-selected set - the result
contradicts QM - but also
proves nothing - the place
-selection is illegitimate since
the results are now constrained
to satisfy Bell by the selection
procedure. It has no bearing
on the question of locality at
all.

Zhai

Our conclusion at this stage is that the EPR experiment has nothing necessarily to do with locality$_3$, it does 'demonstrate' nonlocality$_2$ in a 'conflated' version of QM or nonlocality$_1$ in an 'unconflated' version of QM. In a Copenhagen account it can be said to demonstrate nonlocality$_0$, which may be denied, only Bohr, to be a physical effect at all.

Let us reinforce the fact that locality$_3$ is not involved by the following comments:
Suppose spin-rotor ~~apparatus~~ A is reading a sequence of results + − − + + − + −
– Now hook up ~~apparatus~~ B
This enables us to spin-rotor tag at location B the various results ~~that~~ will be produced at A. But to get a physical effect at A this tagging information would have to be transmitted from B to A e.g. we could then filter out all the − results and get a sequence of + + + + − − − recorded at A. This would indeed be a physical effect (or actual change in the statistics at location A) but this is not what the EPR experiment establishes.
By an example suppose I walk into the lecture theatre at I.C. At that moment you become aware that my room at Chelsea is empty, but to do anything about this, eg to 'tackle' students queuing up at my 'door' in Chelsea

[illegible] would be transmitted the information back to [illegible].

Now what about non-locality [illegible]. Does this violate Einstein causality principle. With static arrangement in which the spin-meters are set well in advance of the particle [illegible] there could be effect [illegible] from the spin-meters to the emerging particles that would not violate Einstein causation. This is the object of Aspect's experiment to change the setting of the spin-meters while the particles are in transit so that there would not be time to transmit an effect from A with velocity ≤ c, before the particle B spin is recorded on its spin-meter.

If the result of the Aspect experiment is positive i.e. to show a different correlation result from the static arrangement then would suggest we are dealing with a [illegible] physical effect transmitted in accordance with Einstein causality from A to B. If not we must either violate Einstein causality condition for micro-systems but would then contradict 'S.R.' the theoretical interpretation for the invariance [illegible] of S.R. provided by the Einstein causality condition as required by those who deny a causal theory of time who believe S.R. allows tachyons etc., and who can deal in some way with the so-called causal loop paradoxes

All these types have been much discussed in the literature since the existence of loopholes was [illegible] proposed as consistent mainly [illegible] by [illegible] & others. The relevance of this work to the EPR Paradox has been discussed by Fox (1972).

With regard to non-locality, Shimony has recently suggested what he calls 'peaceful coexistence', Einstein Causality does not apply to transitions [illegible] → sharp but does apply to sharp → sharp, since this is the only case relevant in the signal discussion of relativity.

With regard to non-locality, this depends on accepting the view that the position of an electron in a non-sharp eigenstate is a meaningless idea, as all the models arise from assuming that there is 'reality' there which then gets changed by measurement on the other particle. This is a possible position, but puts an absolute ban on future ontological speculation which might lead to progress in actual physical theories. Bohr assumed that with QM we had reached a sort of end-point beyond which we could not predict, even at the quantum level. Such prohibitions seem to be [illegible] a bad thing for the future of physics

Insertion

complete

* So complete Treatise on Physics should
really have pages −1 . . . −200 —
explaining everything that is
assumed on p. 1 before we
attempt to build up the
actual applications on pages +1 . . . +200 —

This does not mean we must return to classical-style ontologies — they must be more [illegible], but they postulate [illegible] some features of traditional [illegible] or probability is one way of restoring the notion of objective reality into quantum physics.

This leads me to the final question. What is the correct relationship between physics and philosophy of physics.

Philosophy of any subject may be defined broadly as the study ~~of the~~ [illegible] of concepts, principles, [illegible] presuppositions underlying our a particular branch of knowledge.

There are now 2 parallels

1.) Physical theories should be changed by exposure to philosophical preconceptions about the nature of reality etc.

2.) Philosophical ideas about the nature of reality etc should be modified in the light of physical theories.

With regard to 1) I think it almost [illegible] for philosophers of physics to intrude in theoretical physics — they tend to end up as cranks!

I think the philosophers can contribute to general understanding of a given theory without [illegible] involving raising philosophical positions as in alternative (2) above.

* Cf also Kierkegaard's expositor Høffding and the psychological theories of William James – the difficulty of drawing a line between observer, observed, subjective, objective features of reality

Of course theoretical physicists do use philosophical analyses of a sort in practically their efforts. The remarkable, empirical, historical fact is that the theories ~~so relativity~~ often do not implement the philosophy (this is a interesting feature of C. R.) or the philosophy is very muddled as in the case of Bohr's misreading of Kierkegaard* Kant, Positivism.

~~In a sense Einstein did not understand relativity, nor Bohr QM, but just that one can ride a bicycle without ~~dynamics~~ understanding stability theory in classical mechanics. With that ~~that's~~ deliberately provocative remark, I will bring the talk to a close.~~

~~do physics without understanding it rather like riding.~~

In a sense Einstein did not understand relativity nor Bohr QM ~~but~~ that one can do physics without understanding it rather like riding a bicycle without knowing anything about rigid-body dynamics. With that deliberately provocative remark I will bring this talk to a close.